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by

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**September 1965**

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## CONTENTS

|  | <u>Page</u> |
|--|-------------|
| ABSTRACT . . . . .                                       | v           |
| NOMENCLATURE . . . . .                                   | vi          |
| THE PROBLEM . . . . .                                    | 1           |
| COMPENSATION FOR INCIDENT<br>BEAM POLARIZATION . . . . . | 5           |
| EXPERIMENTAL RESULTS . . . . .                           | 7           |
| OTHER POLARIZERS . . . . .                               | 10          |
| CONCLUSION . . . . .                                     | 11          |
| REFERENCES . . . . .                                     | 12          |

# POLARIZATION OF THE INCIDENT BEAM IN NON-NORMAL REFLECTANCE MEASUREMENTS

by

John K. Coulter

## ABSTRACT

In non-normal reflectance measurements on specular samples large errors can result if the polarization of the incident beam is not taken into account. This polarization can result from reflections off mirrors, refraction in prisms and windows, or from the light source itself. To compensate for the polarization it is not enough to know the intensity ratio of the two orthogonal components in the incident beam. However, correct results can be obtained by averaging the reflectance measurements in two orthogonal planes of incidence (without any knowledge of the amount of incident beam polarization). A simpler method, requiring only one measurement of reflected light, equalizes the two incident components by orienting a polarizing element normal to the beam, with its direction of maximum transmission at  $45^\circ$  to the plane of incidence of the sample. Results are given for aluminum at  $75^\circ$  angle of incidence which shows the agreement between the reflectance of a beam polarized at  $45^\circ$  and the reflectance of a completely unpolarized beam. A discussion of various polarizing elements is presented.

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## NOMENCLATURE

$I_x$  = intensity of that component of the light which is polarized in the x-direction

(subscript x)

H = horizontal direction

V = vertical direction

|| = parallel to plane of incidence of the sample

$\perp$  = perpendicular to the plane of incidence of the sample

45 = 45° to the plane of incidence of the sample

$g = I_{||} / I_{\perp}$

$R_x$  = reflectance of a surface for a light beam polarized in x-direction

$T_x$  = transmittance through an interface for a light beam polarized in the x-direction

$\bar{R}$  = average, or measured, reflectance

$\bar{R}_{\text{unpolarized}}$  = reflectance for natural unpolarized light

$a$  = absorbtance =  $1 - R$  for an opaque material

$N$  = normal to the surface

$A_{45}$  = amplitude of an electromagnetic wave polarized 45° to the plane of incidence of the sample.

## POLARIZATION OF THE INCIDENT BEAM IN NON-NORMAL REFLECTANCE MEASUREMENTS

### THE PROBLEM

In almost all commercial spectrophotometers equipped with reflectance attachments no caution is suggested for polarization of the incident beam. Since most of these instruments take measurements only at near-normal incidence the polarization problem is negligible. However, in studying spacecraft coatings, it is often desirable to measure the reflectance at large angles of incidence. In these cases accurate measurements can only be obtained if explicit provision is made for the polarization of the incident beam, or if the polarization is fortuitously small. If the expression for the measured reflectance is written in terms of the components parallel and perpendicular to the plane of incidence, the effect of the beam polarization is readily apparent:

$$\begin{aligned}\bar{R} &= \frac{I_{||} R_{||} + I_{\perp} R_{\perp}}{I_{||} + I_{\perp}} \\ &= \frac{R_{||} + g R_{\perp}}{1 + g}\end{aligned}\tag{1}$$

when  $g = 1$  the reflectance by definition is that for an unpolarized beam, but when  $g \neq 1$  the  $g$ -value distorts the relative weight of  $R_{\perp}$  in the average reflectance.

As an example of absorptance determinations on a typical spacecraft coating (evaporated aluminum) Table I shows that large errors result at large angles of incidence for a not-uncommon  $g$ -value of  $1/2$ . Of course there is no error at normal incidence because the parallel and perpendicular components are undefinable. But at  $45^\circ$  there is an error of 10.7%, and at  $75^\circ$  the error is 27.0%

TABLE I. Calculation for Aluminum at  $\lambda = 0.45 \mu$ 

| $\theta$ | $g = 1$   |       | $g = 1/2$  |       | $\frac{a' - a}{a}$ |
|----------|-----------|-------|------------|-------|--------------------|
|          | $\bar{R}$ | $a$   | $\bar{R}'$ | $a'$  |                    |
| 0        | .9266     | .0734 | .9266      | .0734 | 0                  |
| 30°      | .9260     | .0740 | .9225      | .0775 | .047               |
| 45°      | .9233     | .0767 | .9151      | .0849 | .107               |
| 60°      | .9152     | .0848 | .8993      | .1007 | .188               |
| 75°      | .8995     | .1005 | .8724      | .1276 | .270               |

The hypothetical case of one component of the incident beam being only half of the other component is not unrealistic as every optical element in the system can contribute to the polarization. The schematic of a Perkin-Elmer model 99 monochromator in Figure 1 shows that there are 11 non-normal metallic reflections and 8 non-normal traversals through an air-dielectric interface (at the prism). In the former case the perpendicular component ( $I_v$ ) is dominantly reflected at each surface. In the latter case, more of the perpendicular component is reflected out of the beam so that the parallel component ( $I_H$ ) is larger. The net result from this monochromator is that the horizontal component tends to dominate.

If viewed non-normally, the light source itself produces some polarization in the beam, especially if it is an incandescent tungsten ribbon. Figure 2a shows a vertical ribbon source viewed non-normally. Although some light originates at the ribbon surface, much of the light radiates from atoms in the interior near the surface. At the metal-air interface (Fig. 2b) more of the perpendicular component is reflected back so that the parallel component ( $I_H$ ) tends to dominate. For our reflectometer the change in beam polarization was measured for the light source-monochromator combination as the vertical tungsten ribbon was rotated from normal-to-optical axis to roughly 45°-to-optical axis. The  $g$ -values changed from 0.72 to 0.45, respectively, at  $\lambda = 0.54\mu$ .

Of course a gas discharge source would introduce less beam polarization.

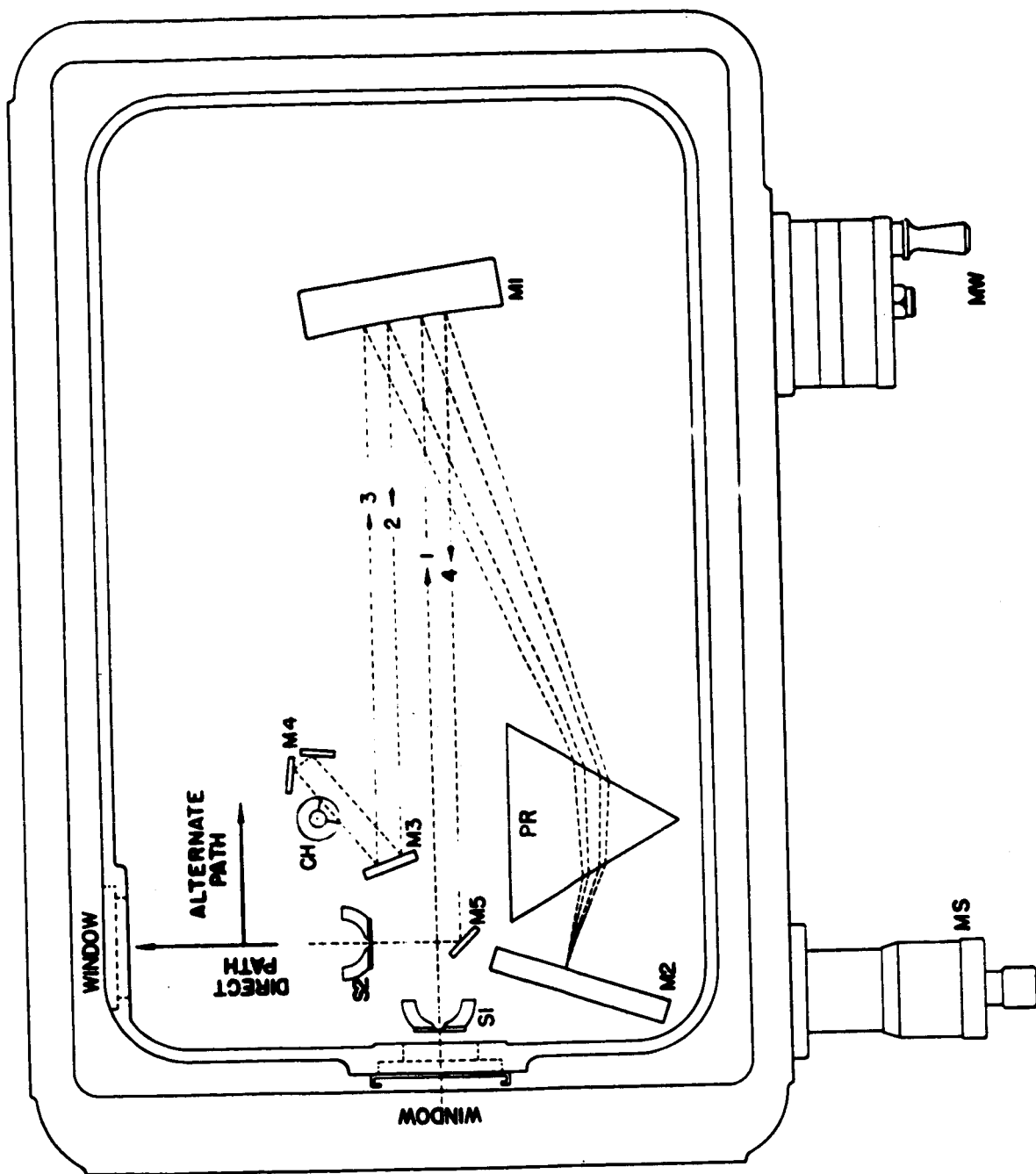


Figure 1—Schematic optical path of the Model 99 Double Pass Monochromator



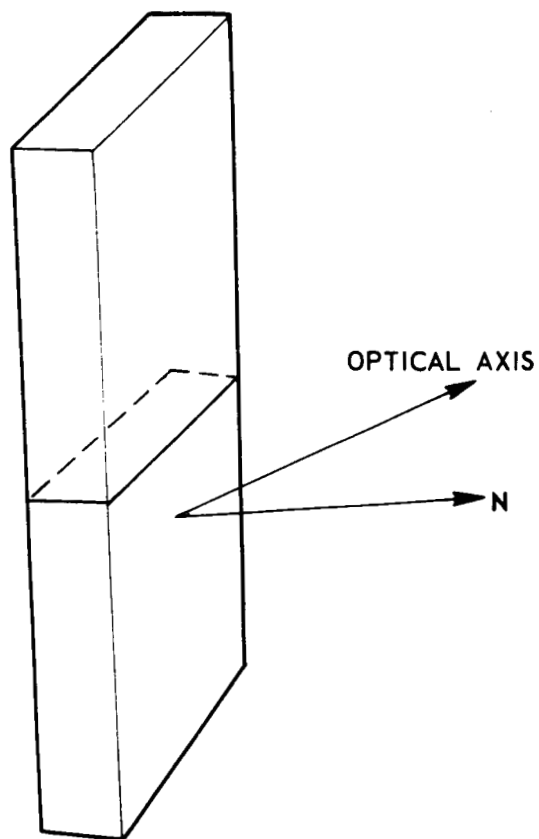


Figure 2a—A vertical incandescent ribbon source viewed non-normally

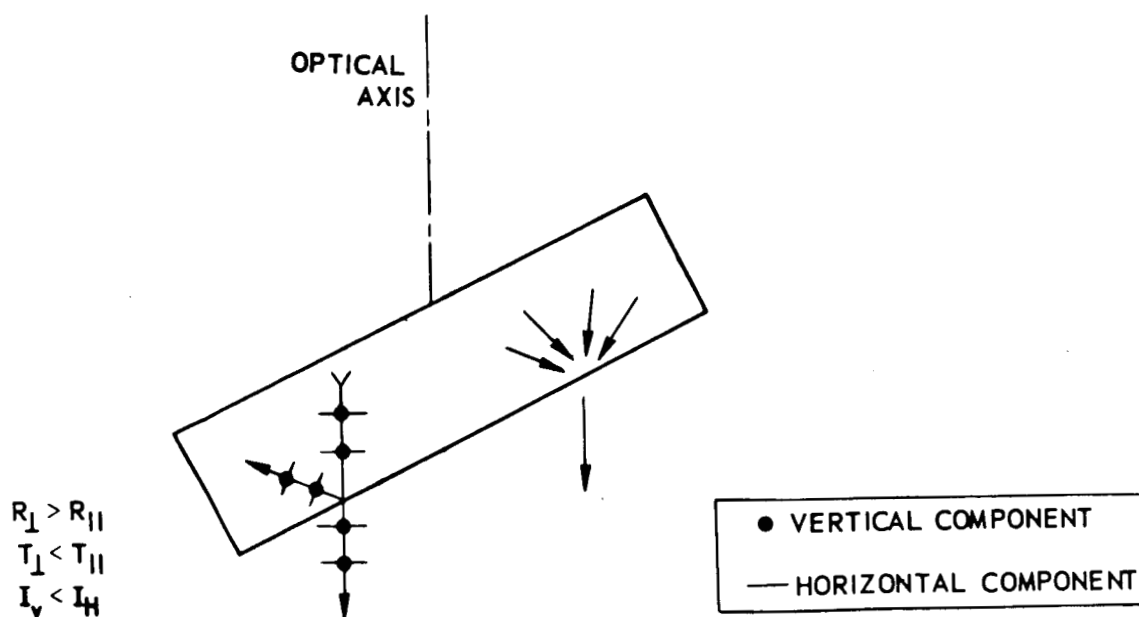


Figure 2b—Cross-section of the ribbon source

## COMPENSATION FOR INCIDENT BEAM POLARIZATION

In an attempt to make corrections for polarization of the incident beam in subsequent reflectance measurements one can experimentally determine the intensity ratio of the 2 orthogonal components in the incident beam at all wavelengths. However, the  $g$ -value is not sufficient information to calculate the unpolarized reflectance (equation 2) from the measured reflectance (equation 1).

$$\bar{R}_{\text{unpolarized}} \equiv \frac{R_{||} + R_{\perp}}{2} \quad (2)$$

There are 2 equations, but 3 unknowns:  $R_{||}$ ,  $R_{\perp}$  and  $\bar{R}_{\text{unpolarized}}$ .

There are two methods by which the unpolarized reflectance can be obtained, which do not require explicit knowledge of the  $g$ -values. The first method is readily practicable with the absolute-reading Gier-Dunkle Integrating Sphere (GDIS) system. If the sample and detector are capable of being rotated as a unit through  $90^\circ$  about an axis in line with the direction of propagation of the incident beam, the parallel component in one orientation becomes the perpendicular component in the other, and vice versa (Figure 3). The two measurements of reflectance are

$$\bar{R}(1) = \frac{I_H R_{||} + I_V R_{\perp}}{I_H + I_V} \quad (3)$$

and

$$\bar{R}(2) = \frac{I_H R_{\perp} + I_V R_{||}}{I_H + I_V} \quad (4)$$

The average of  $\bar{R}(1)$  and  $\bar{R}(2)$  is seen to be equal to the unpolarized reflectance:

$$\frac{\bar{R}(1) + \bar{R}(2)}{2} = \frac{R_{||} + R_{\perp}}{2}$$

This method requires 3 measurements: 2 of reflected light and 1 of incident light (since the denominators of equations (3) and (4) are identical).

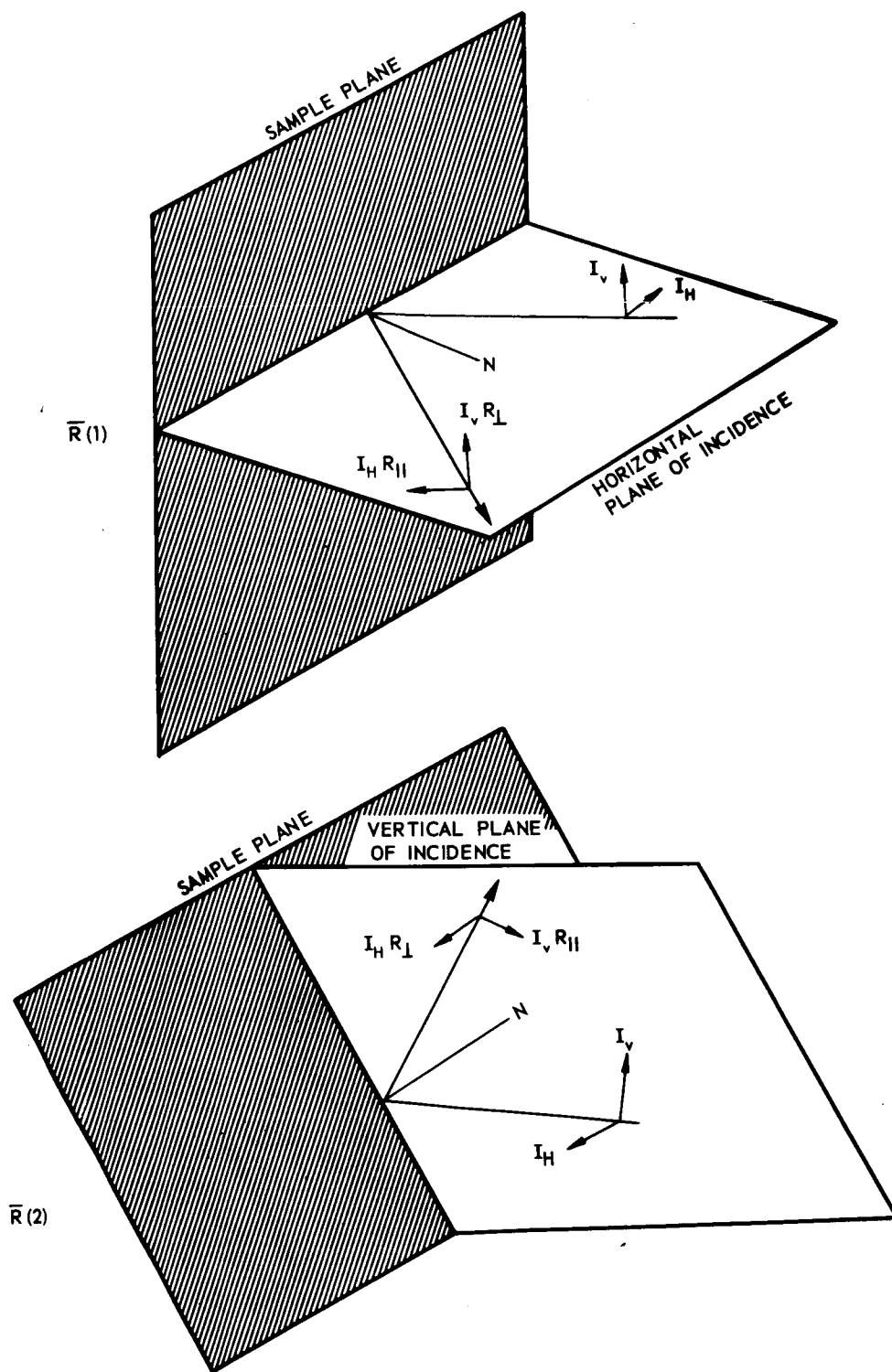


Figure 3—Reflectance in 2 orthogonal planes of incidence

The second method requires that the 2 components in the incident beam be equalized by making the incident beam completely linearly polarized at  $45^\circ$  to the plane of incidence. This is achieved by orienting a polarizing element normal to the beam with its direction of maximum transmission at  $45^\circ$  to the plane of incidence. The linearly polarized light emerging from the polarizer can be resolved into 2 equal components parallel and perpendicular to the plane of incidence. See Figure 4, where  $k_1$  is the transmittance for light completely polarized in the direction of maximum transmission of the polarizer, and  $k_2$  is the minimum transmittance. Since the incident beam is linearly polarized, the light reflected off the sample will be elliptically polarized in general. The intensity of this elliptically polarized light is equal to the sum of the squares of the amplitude of each component:

$$I_R = R_{||} A_{45}^2 \cos^2 45^\circ + R_{\perp} A_{45}^2 \cos^2 45^\circ$$

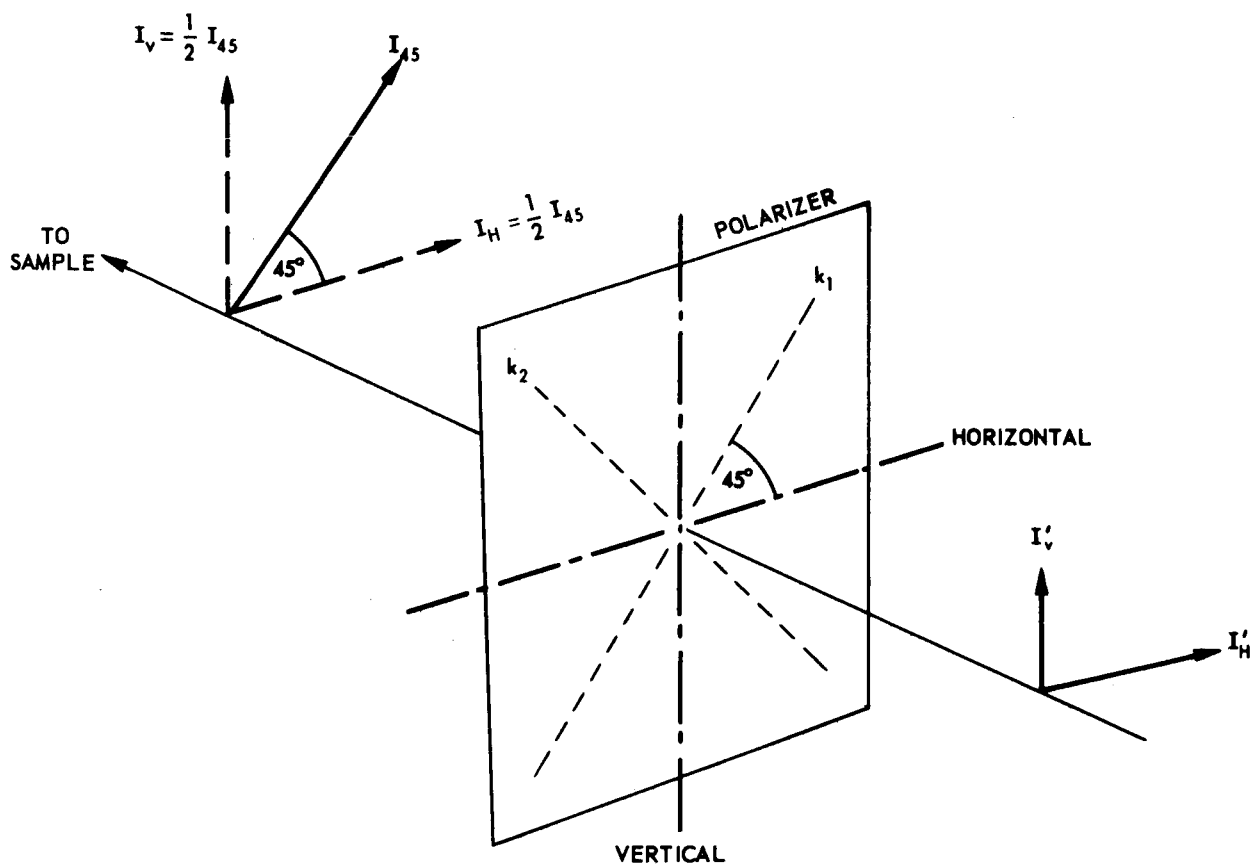
$$= \frac{1}{2} (R_{||} + R_{\perp}) I_{45}$$

(the phase shift between the 2 components does not affect the intensity). Thus the ratio of reflected to incident intensities is identically equal to the unpolarized reflectance.

In our reflectometer at Goddard (GDIS system) the beam used to measure the intensity of the incident light is rotated by about  $40^\circ$  from the beam measuring the reflected light (see Figure 5). In order to place the polarizer normal to both beams it was necessary to place it ahead of the transfer optics. The subsequent polarization due to reflections off the 2 aluminized mirrors at angles of incidence of  $20^\circ$  and  $10^\circ$  was calculated to produce negligible error in the measured reflectance. The  $g$ -value of the resultant beams was  $< 0.97$ , producing a relative reflectance error  $< 0.2\%$ ; much smaller than the limit of accuracy of the instrument itself.

## EXPERIMENTAL RESULTS

We have used polaroid plastic laminate as the polarizer because of its low cost, large aperture and small thickness. HN22 was used in the visible region, HN38 was used in the ultraviolet (where the available light is less) because of its higher transmission even though its polarizing ability is less, and HR was used in the infrared. The laminate was taped to an aluminum disk and mounted on a collar between the monochromator and the transfer optics case.



THE PLANE OF INCIDENCE IS ASSUMED TO BE EITHER VERTICAL OR HORIZONTAL.

$$I_H = I_V = (A_{45} \cos 45^\circ)^2 = \frac{1}{2} I_{45}.$$

Figure 4—Production of equal components with a polarizer

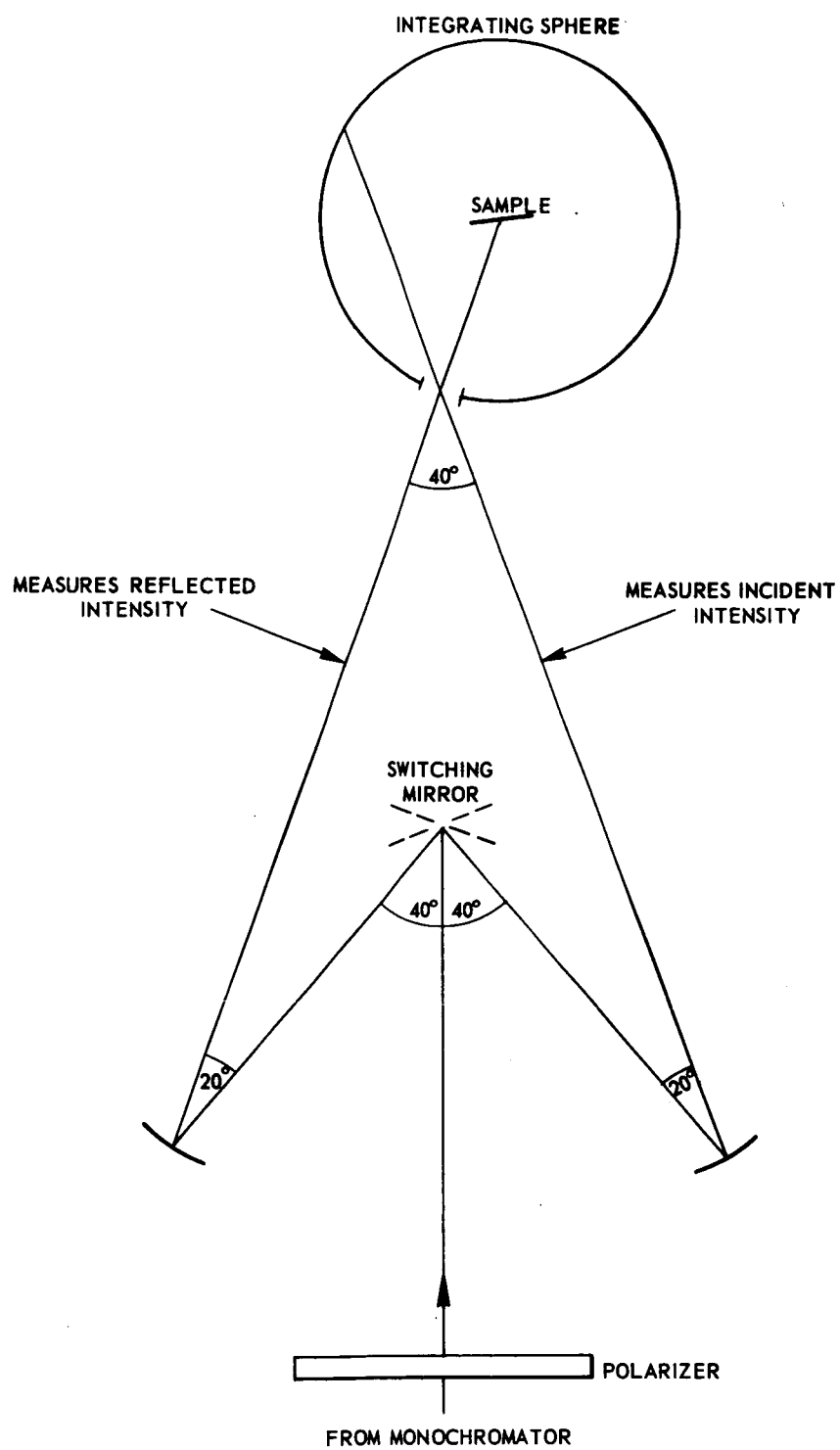


Figure 5-GDIS transfer optics

The accuracy of orientation of the direction of maximum transmission was estimated to be  $\pm 3^\circ$ . As a demonstration of the ease of this method the reflectance of an evaporated aluminum sample at an angle of incidence of  $75^\circ$  was measured with the polarizer azimuth at  $45^\circ$ ,  $R_{45}$ . This was compared with the average of the measured reflectances,  $\bar{R}$  (equal to the unpolarized reflectance), for the incident light completely polarized alternately in the vertical and horizontal planes (see Table II).

TABLE II. Measurements for Aluminum at  $\theta = 75^\circ$ .

| $\lambda(\mu)$ | $\bar{R}$ | $R_{45}$ | $(R_{45}/\bar{R})$ | $g$ |
|----------------|-----------|----------|--------------------|-----|
| 0.39           | .914      | .918     | 1.004              | .75 |
| 0.46           | .902      | .907     | 1.006              | .72 |
| 0.55           | .881      | .881     | 1.000              | .72 |
| 0.65           | .860      | .866     | 1.007              | .71 |
| 0.75           | .822      | .824     | 1.002              | .75 |
| 0.90           | .856      | .863     | 1.008              | .68 |
| 1.12           | .928      | .934     | 1.006              | .58 |
| 1.29           | .944      | .946     | 1.002              | .56 |
| 1.54           | .940      | .947     | 1.007              | .55 |
| 1.82           | .934      | .941     | 1.007              | .55 |

There is very good agreement between  $R_{45}$  and  $\bar{R}$  at all wavelengths. The slight systematic discrepancy is believed to be due to inaccuracy in positioning the polaroids rather than from polarization in the transfer optics. The  $g$ -values measured for the beam emerging from the monochromator are for the lamp ribbon-filament nearly perpendicular to the optical axis. It is seen that the incident beam was more highly polarized in the infrared region than the visible. We have made no calculations to see why this is true.

## OTHER POLARIZERS

We have used Polaroid plastic laminate for the reasons mentioned above, but other polarizers are available. Table III summarizes the properties of various types. The overall transmission is indicated by the value of  $k_1$  and the degree of polarization is indicated by the ratio  $k_1/k_2$  (reference 1 - Chapter 4, 5 and 6).

TABLE III. Properties of Various Polarizers

| TYPE & EXAMPLE            | $\lambda$ RANGE ( $\mu$ ) | $k_1$ | $k_1/k_2$ |
|---------------------------|---------------------------|-------|-----------|
| POLAROID PLASTIC LAMINATE |                           |       |           |
| HN 38                     | 0.37-0.75                 | 0.8   | $>10^2$   |
| HN 22                     | 0.37-0.75                 | 0.4   | $>10^4$   |
| HR                        | 0.7-2.3                   | 0.7   | $>50$     |
| PRISMS                    |                           |       |           |
| Glan-Thompson             | 0.24-3.0                  | 0.5   | $>10^5$   |
| Taylor-modified           | 0.24-3.0                  | 0.9   | $>10^5$   |
| Glan-Foucault             |                           |       |           |
| PILE-OF-PLATES            |                           |       |           |
| LiF                       | UV                        | —     | $>100$    |
| glass                     | VIS                       | —     | $>100$    |
| AgCl, Se, etc.            | IR                        | —     | $>100$    |

Polaroid plastic laminate is readily available in sheets  $12'' \times 12''$ . Polarizing prisms usually have an aperture  $\sim 15 \text{ mm} \times 15 \text{ mm}$  and length  $\sim 3 \text{ cm}$ . Their cost is high but they can produce the highest degree of polarization. Shurchiff and Ballard (ref. 2, p.48) estimate that the main reason why  $k_1/k_2$  is no higher than  $10^5$  for a well constructed prism is because of the experimental difficulties in measuring this quantity. Pile-of-plates polarizers are chiefly useful for the wavelength regions where the other types fail to transmit, viz. the far UV and the intermediate and far IR. Their degree of polarization depends on the number of plates actually used.

## CONCLUSION

We have demonstrated a simple method, requiring only a single orientation of a polarizing element, which produces non-normal reflectance values equivalent to those for an unpolarized incident beam. This orientation remains constant for all angles of incidence and for all wavelengths over which the polarizer operates. The method requires only a measurement of the incident intensity and one measurement of the reflected intensity for each datum point. This time-saving feature is useful when large numbers of samples, or angles, are to be measured.



## REFERENCES

1. Polarized Light: Production and Use by W. A. Shurcliff, 207 pp. Harvard Univ. Press. Cambridge, Mass. 1962
2. Polarized Light by W. A. Shurcliff and S. S. Ballard, 144 pp. Van Nostrand Princeton, N. J. 1964.